TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 237

PROPELLER DESIGN

A SIMPLE SYSTEM BASED ON MODEL PROPELLER TEST DATA - III

By Fred E. Weick
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Summary

This report, the third of a series of four, describes a
simple system for designing propellers of a standard form.
In this report, the system is based on tests of a family of
model propellers of standard Navy form, the data from which
have been extended by means of calculations to cover the com-
plete range likely to be found in practice. However, it can
be worked out for any family having propellers of one general
form. This system can also be applied as given to propellers
of different forms by means of form factors. Modifications
are made for full scale flight conditions, i.e., the particular
tip speed of the propeller, and body or fuselage interference.

Introduction

The full blade element theory is not convenient for the
designing of propellers. Its use involves a great deal of
calculation. Furthermore, it merely analyzes the characteris-
tics of a propeller for a given set of conditions but does not
design one to fit certain requirements. If a standard form of

propeller is to be designed, it is much more convenient to con-
sider the characteristics of the propeller as a whole. These
can be plotted in the form of curves covering the full range of
propellers likely to be used.

The model propeller tests upon which this system is based
are described in N.A.C.A. Technical Report No. 237, entitled
"Tests on Thirteen Navy Type Model Propellers," by W. F. Durand.
A family of only thirteen Navy models was tested, which neces-
sarily covered but a small portion of the whole range of pro-
pellers of this form. In order to cover all extremes of pitch
ratio, aspect ratio, and thickness or camber ratio likely to
be needed in practice, the original family was extended by
means of calculations with the blade element theory according
to the method described in N.A.C.A. Technical Note No. 236.
This extended family was then used as the basis from which the
main design curves were drawn.

It is believed that the powers absorbed by standard wood
propellers can be calculated more accurately than the horse-
powers of service engines can be determined in flight, which
is within 4 or 5 per cent.

Use of Model Data in Design

Table I contains a list of symbols used in the following
discussion.

The data provided the propeller designer are the horsepower

of the engine, the revolutions per minute of the propeller shaft, and the air speed of the airplane. These comprise the required performance of the propeller with its combination of airplane and engine. A non-dimensional coefficient involving the above factors is $\sqrt{\dfrac{\rho V^5}{P\,n^2}}$. This relation is developed in N.A.C.A. Technical Report No. 186 (Reference 1). It is called the speed-power coefficient and designated by K_s. In engineering units and with the value of ρ for standard conditions,

$$K_s = .325 \sqrt{\frac{(\text{M.P.H.})^5}{\text{HP.} \times N^2}}$$

A nomogram for the solution of this equation will be found in Fig. 8.

Values of K_s can be found for the model test data from the relation,

$$K_s = \sqrt{\frac{\left(\dfrac{V}{nD}\right)^5}{C_p}} \ .$$

The operating conditions of any propeller are governed by the air speed, the revolutions, and the propeller diameter. These are put into another dimensionless coefficient sometimes called the slip function, or V/nD. Expressed in engineering units, V/nD becomes $\dfrac{88 \times \text{M.P.H.}}{ND}$.

If the nominal slip of a propeller is designated by s,

$$1 - s = \frac{V}{nP} = \frac{\dfrac{V}{nD}}{P/D} \ .$$

For both purposes of design and analysis it has been found

most convenient to use curves of constant $1 - s$ plotted with V/nD as ordinates and K_s as abscissas. A series of such curves can be plotted on one sheet for propellers of varying P/D ratio, but of constant AR and CR. If a separate graph is drawn for each combination of AR and CR, the number required becomes excessive. It is therefore advisable to chart a single series of constant AR and CR, and give corrections for AR and CR in two other charts.

The speed power coefficients for this basic series with $AR = 6$ and $CR = 1$ obtained from the extended model test data are called K_s'. Fig. 1 is a chart of K_s' and V/nD for constant values of $1 - s$. It is plotted on special logarithmic scales for convenience. The variations of K_s from K_s' for different aspect ratios and camber ratios are charted in Fig. 2 and Fig. 3, respectively. These three sets of curves are the main design and analysis tools of this system.

The efficiency curves for the basic series of $AR = 6$ and $CR = 1$ are given in Fig. 4. Corrections to this efficiency for other aspect and camber ratios are in Figs. 5 and 6. The use of the curves is described in the next section.

Procedure in Analyzing the Performance of a Propeller

The analysis of standard Navy propellers is made relatively simple in Table II. The propeller name or number, airplane, engine, R.P.M., M.P.H., diameter, pitch, AR, and CR are ob-

tained from the test data and the propeller drawing. If the brake horsepower is not given in the test data, it can be obtained fairly accurately from full throttle power curves for the type of engine used. The P/D, V/nD, and $1 - s$, are then calculated as shown on the form, and the speed power coefficient K_s', is obtained from Fig. 1. This is not necessarily the K_s for the exact propeller being analyzed, and must be modified for AR and CR. The AR correction is found in Fig. 2, from a simple curve. The CR correction is somewhat more complicated, depending on the slip, the P/D, and the CR (Fig. 3). First the $1 - s$ is located on the left-hand scale and run over to the point where it intersects the proper P/D. From this point a vertical line is run to the CR curve and the correction factor is read on the scale to the right. The corrected speed power coefficient for the propeller is then $K_s = K_s' \times$ AR cor. $\times$ CR cor.

The torque horsepower is then found from the nomogram of the speed power coefficient equation in Fig. 8. A straight edge is run through K_s and M.P.H. to the reference line. It is then run from the point of intersection on the reference line through the R.P.M. and the point where it crosses the HP. scale gives the required Q.HP.

The form factor is a correction to be applied in cases where propellers not conforming to the standard are used. For standard Navy wood propellers this is always unity and may be

disregarded. For other propellers it depends on the plan form, camber ratio curve, and the distribution of the pitch along the radius. The Q.HP. multiplied by the form factor is called the calculated HP. or C.HP. In the case of standard Navy propellers, this is of course the same as the Q.HP.

Unless the analysis has been made for a model propeller without body or fuselage interference, the brake horsepower of the engine should be greater than the calculated horsepower by an amount depending on the tip speed, the body interference, and the distortion of the propeller blades in action. The distortion is considered small in standard Navy wood propellers. The greatest part of this difference in power is thought to be due to a scale effect which varies with the tip speed. An account of this scale effect is given in N.A.C.A. Technical Note No. 225 (Reference 2). The data as used for design and analysis work are given in Fig. 7. The ratio of B.HP./C.HP. found in the analysis should correspond to that given for the proper tip speed in Fig. 7.

The efficiency is found by means of Figs. 4, 5, and 6, the corrected efficiency being the product of the three values.

When propellers of other than standard Navy form are analyzed, it is sometimes necessary to use the complete blade element theory. If this is used with the section characteristics given in N.A.C.A. Technical Note No. 235, the results should be the same as if a model of the propeller were tested in a wind

tunnel. However, if the propeller be built of wood along con-
ventional lines, and with approximately uniform pitch, the meth-
od of analysis in Table II can be used with fair accuracy. In
that case the pitch, AR, and CR are based on the section at
75 per cent radius, and are approximate average values for the
propeller.

An example of a standard analysis is shown in Table II.

Procedure in Designing a Propeller

Table III is used for following through the design of stand-
ard Navy propellers.

The following information should be furnished the designer:

1. Airplane and Purpose.

2. Engine.

3. Rated HP. at above R.P.M.

4. Revolutions per minute.

5. Speed of advance for which propeller is to be designed.

6. Maximum allowable propeller diameter.

The first step in the design is to determine the approxi-
mate diameter. This is necessary in order to obtain the ap-
proximate tip speed upon which the B.HP./C.HP. factor depends,
and approximate 1 - s and P/D upon which the CR correc-
tion factor depends.

The approximate diameter may be obtained from the equation

$$D = K \sqrt[4]{\frac{HP.}{N^2 \times M.P.H.}}$$. The solution of this is facilitated by

the use of the nomogram in Fig. 9, which also gives values of

the constant K for various conditions. It may, however, be

preferable to judge the diameter by comparison with some known

propeller operating under similar conditions.

If the maximum allowable diameter is less than the approx-

imate value, the former is taken as the final diameter, and a

slightly different method of procedure is followed, which is

explained later.

With the approximate diameter established, the approximate

V/nD, or $\frac{88 \times M.P.H.}{ND}$ is found. This is used to determine

the P/D in Fig. 10. The P/D will vary a considerable amount

depending on whether a high speed, climbing, or general service

propeller is desired. In entering the curves in Fig. 10, the

V/nD should be modified according to the camber ratio as noted

on the sheet. The reason for this is that the dynamic pitch of

thick propellers is greater than that of thin propellers, just

as the angle of no lift for thick airfoil sections is less than

that for thin sections. The thin sections have their best L/D

at a larger angle of attack, and the thin section propellers

work at their maximum efficiency at higher slips.

With the approximate P/D selected, 1 - s is found from

the relation

$$1 - s = \frac{V/nD}{P/D} .$$

The approximate tip speed in the plane of rotation is then found by means of the equation

$$\text{Tip speed} = \pi n D = .0524 \, ND.$$

This value is used in Fig. 7 to find the ratio of brake horsepower to calculated horsepower, modification of the ratio being made for body interference.

The form factor is unity for Navy standard wood propellers. For other propellers, it depends on the plan form, the camber ratio curve, and the distribution of pitch along the radius. The form factor may be found for any propeller of special shape by comparing its power as found by means of the blade element theory with that absorbed by a propeller of standard form operating under the same conditions.

The Q.HP. is given by the relation

$$Q.HP. = \frac{B.HP.}{\text{Form factor} \times B.HP./C.HP.}$$

and this value is used in the nomogram of Fig. 8 to solve for K_s, the speed-power coefficient.

Normally, if the diameter is not limited and if there are no strength limitations, it is usually desirable to design propellers with AR = 6 and CR = 1. If the diameter is limited, it may be necessary to decrease the AR or increase the CR, or both. This necessarily entails a decrease in the efficiency. Strength limitations may also require widening and thickening

the blade, sometimes even necessitating a change in the camber
ratio distribution.

The AR and CR having been chosen, the corrections are
found from Figs. 2 and 3. The speed power coefficient for the
basic series propeller (AR = 6 and CR = 1) operating at the
same values of M.P.H., N, D, and P, is then found from the
equation

$$K_s' = \frac{K_s}{AR \text{ correction} \times CR \text{ correction}} .$$

With K_s' and $1 - s$ known, the real value of V/nD is
found from Fig. 1.

The diameter is then determined by the equation

$$D = \frac{88 \times M.P.H.}{N \times \frac{V}{nD}} .$$

If this diameter is within 5 per cent of the approximate
diameter, it may be considered as final. If the difference is
more than 5 per cent, or if extreme accuracy is desired, the cal-
culations should be repeated, using the calculated diameter as
the approximate value in the second computation.

The P/D and pitch are found from $1 - s$ and the final
V/nD.

Considering the case where the diameter is limited, it is
fixed to start with, and one solution only is required. The
final value of V/nD is fixed at the beginning, as is the tip
speed. The same steps are taken as in the previous case up to

and including the solution of K_s in Fig. 8. Then K_s' is found from Fig. 1, using the values of V/nD and $1 - s$.

The AR and CR must make up the difference between K_s and K_s' as determined by the relation

$$\text{AR correction} \times \text{CR correction} = \frac{K_s}{K_s'}$$

This difference may be compensated for by either decreasing the AR or increasing the CR, there being little choice until AR = 5 or CR = 1.2 is reached. It is not usually desirable to design two-bladed propellers with aspect ratios of less than 4.5 or 5, or four-bladed propellers with aspect ratios greater than about 3.5. As three-bladed wooden propellers are not practicable, to make or handle, the CR should be so chosen that aspect ratios of 3.5 to 4.5 or 5.0 can be avoided. With the selection of the AR and CR the design is completed.

An example of a standard propeller design is given in Table III.

Conclusions

The method of propeller design described in this note has been used with very satisfactory results in the Bureau of Aeronautics, Navy Department. With its use the time required for designing a standard propeller has been reduced to a minimum. This is because the characteristics of propellers as a whole are considered instead of the properties of their various sec-

tions. The system is above the average in accuracy due to the
quantity of test data available on standard Navy Propellers.

References

1. Diehl, Walter S. : The Application of Propeller Test
                        Data to Design and Performance Cal-
                        culations. N.A.C.A. Technical Report
                        No. 186. (1924)

2. Weick, Fred E.   : Propeller Scale Effect and Body Inter-
                        ference. N.A.C.A. Technical Note No.
                        225. (1925)

TABLE I.

Explanation of Terms

D — Diameter of propeller in feet.

P — Geometrical Pitch. Distance propeller will advance in one
    revolution without slip, in feet. Uniform pitch indi-
    cates same pitch at all radii.

R — Tip Radius in feet = $\frac{D}{2}$.

r — Radius of any section of propeller in feet.

C — Maximum blade width in feet.

b — Blade width at any section in feet.

AR — Aspect Ratio. For the whole propeller as used in design-
    ing, AR = D/CB. For one blade, as used in stress calcu-
    lations, AR = R/C.

CR — Camber Ratio of propeller blade as a whole. This is the
    ratio of the thickness of the entire propeller blade to
    that of a standard blade, the variation of thickness
    along the radius being the same for all blades. (The
    standard variation of section thickness ratio along the
    radius is shown in Fig. 11. A propeller having this
    distribution of thickness ratio is said to have a camber
    ratio of 1. If the curve is increased by 10 per cent at
    every point, the camber ratio, or CR, is 1.1.)

B — Number of blades in propeller.

V — Velocity of airplane in ft./sec.

TABLE I (Cont.)

M.P.H. – Velocity of airplane in m./hr.

   n – Revolutions of propeller per second.

   N – Revolutions of propeller per minute.

B.HP. – Brake horsepower of engine.

Q.HP. – Torque horsepower – calculated or equivalent model

      horsepower without considering form factor.

C.HP. – Calculated horsepower considering form factor. This

      power differs from the B.HP. by an amount depending

      on the tip speed, fuselage interference, and distor-

      tion of the propeller.

T.HP. – Thrust horsepower.

   η – Efficiency.

  h_U – Maximum upper camber of section.

  h_L – Maximum lower camber of section.

 h/b – Camber ratio of any section.

  C_p – Power coefficient of propeller.

$$C_p = \frac{P}{\rho}\, n^3\, D^5$$

where   P = power in ft.lb./sec.

  K_s – Speed-power or performance coefficient of propellers.

$$K_s = \sqrt{\frac{\rho V^5}{P n^2}} = \sqrt{\frac{\left(\frac{V}{nD}\right)^5}{C_p}}$$

  $K_s{}'$ – Speed-power coefficient for propellers of AR = 6 and

      CR = 1.

TABLE I (Cont.)

s - Nominal slip, based on the relation $1 - s = \dfrac{V}{nP}$.

ρ - Mass density of air. This may be taken as .00237 for

sea level and standard atmosphere.

Tip speed -- The distance traveled by the tip of the propeller

in unit time in the plane of rotation.

Tip speed = π nD = .0524 ND ft./sec.

Rotation - A right-hand propeller turns clockwise and a left-

hand propeller turns counterclockwise when viewed

from a point in the slip stream of the propeller.

TABLE II.

Standard Propeller Analysis

Propeller	No. 631	⎫
Airplane	DT-4	
Engine	T-2	
B.HP. (from Engine data)	545	
R.P.M.	1830	
M.P.H.	112.2	
Diameter in feet	10.0	⎬ Information required.
Pitch at 75% rad. in feet	6	
$AR = \dfrac{9.5\ D(ft.)}{B \times b(in.)\,at\ 75\%\ rad.}$	6	
$CR = \dfrac{h}{.107\ b}$ for 75% rad.	1.1	
P/D	.60	⎭
$\dfrac{V}{nD} = \dfrac{88 \times M.P.H.}{n\ D}$	.539	⎫
$1 - s = \dfrac{V}{nD}\Big/\dfrac{P}{D}$	.90	
K_S' from Fig. 1	1.17	
AR correction from Fig. 2	1	
CR correction from Fig. 3	.951	⎬ Steps in Analysis
$K_S = K_S' \times$ AR cor. $\times$ CR cor.	1.11	
Q.HP. from Fig. 8	465	
Form factor, Fig. 12	1	
Corrected Q.HP. or C.HP.	465	⎭

TABLE II (Cont.)

$\dfrac{\text{B.HP.}}{\text{C.HP.}}$	1.17
Tip speed in ft./sec. =	
.0524 ND	960
Efficiency'	.739
AR correction	1
CR correction	.995
Corrected Efficiency	.735

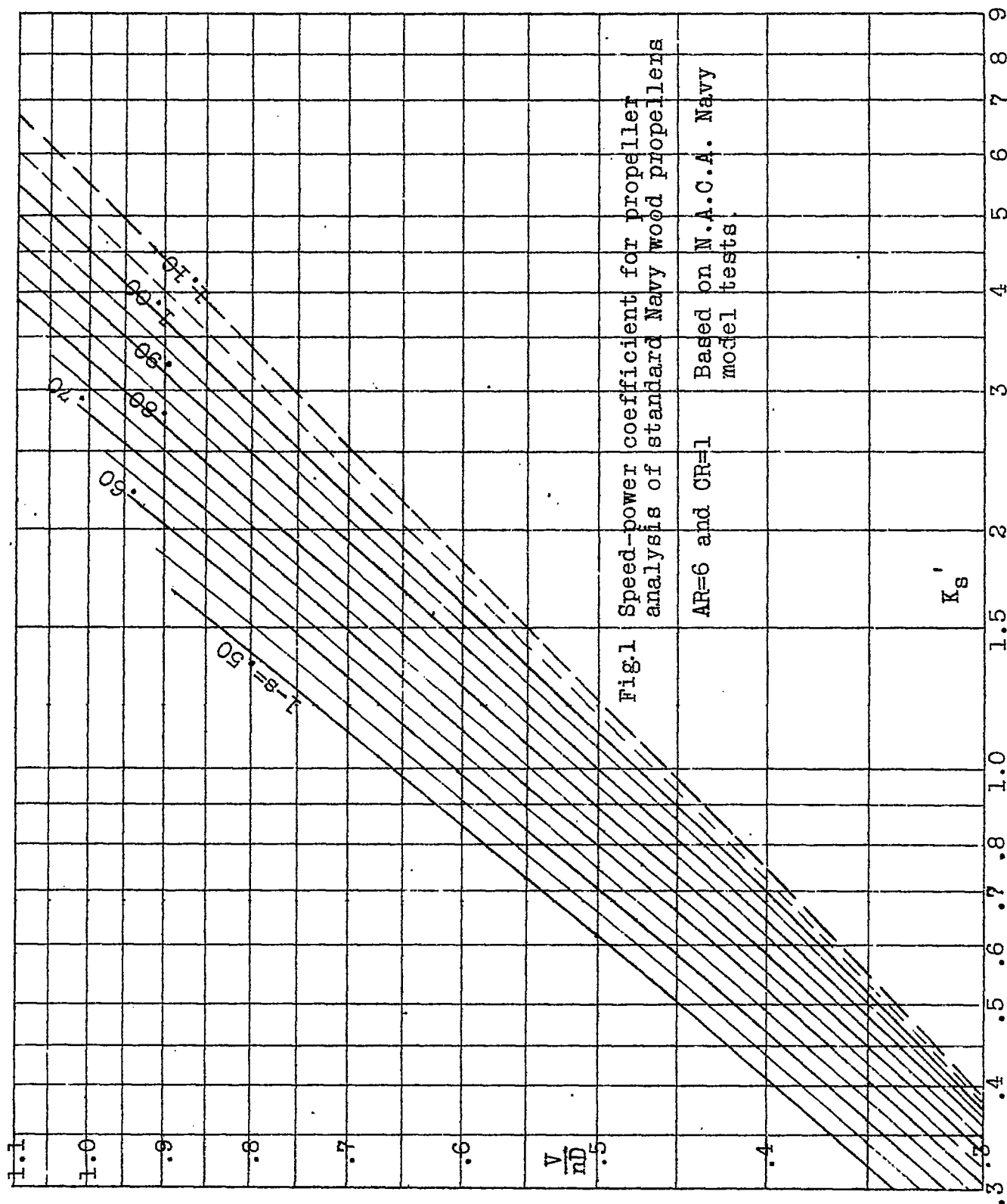These should check the curve in Fig. 7 within 2%.

TABLE III.

Standard Propeller Design
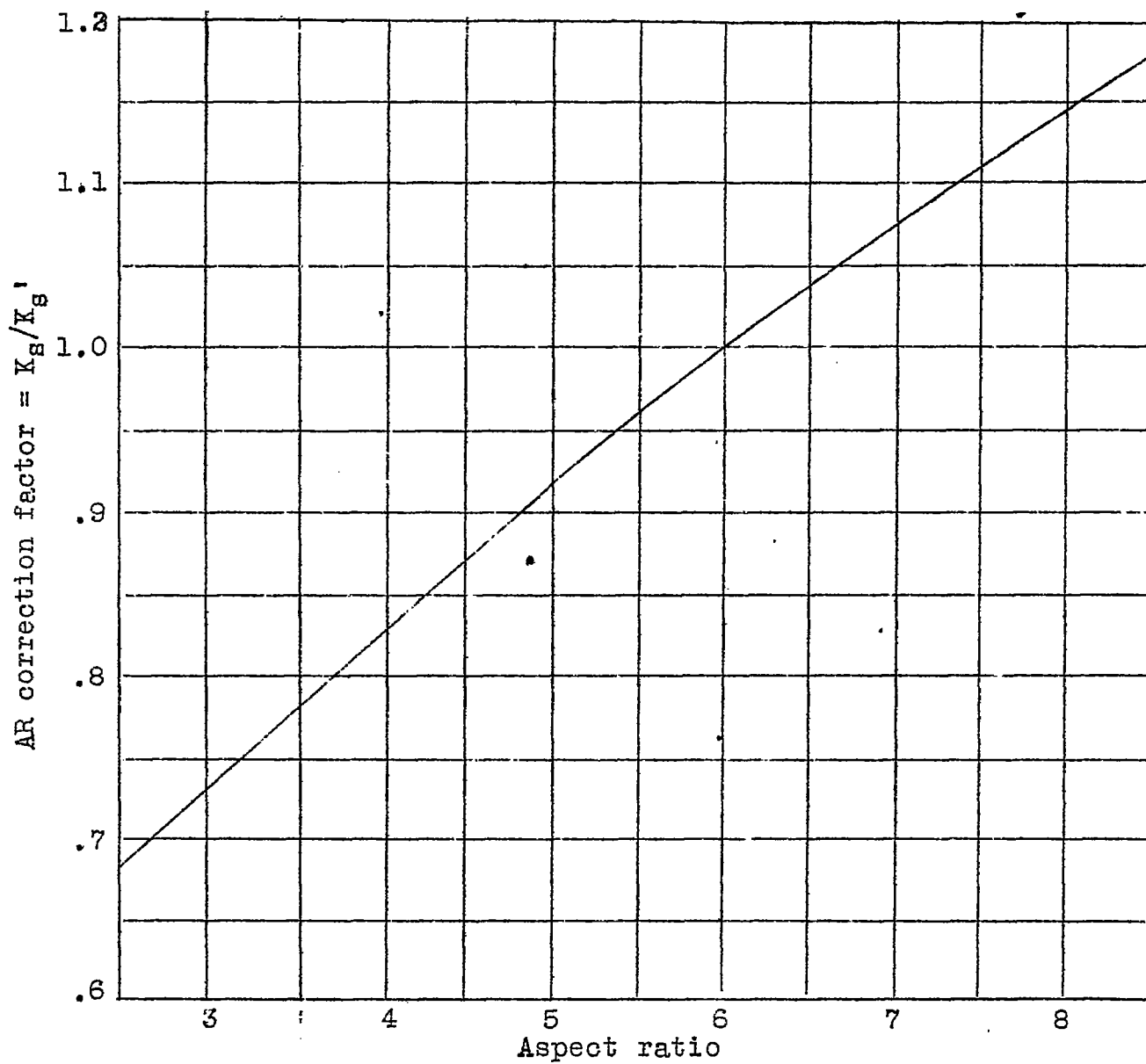
Type of Propeller – wood.   Final dia. =8.26 ft.   AR = 7

Engine – J–4.   Airplane – UO–1.   Final pitch=6.11 ft.   CR = 1.2

	Approx.	Final	Approx.	Final
B.HP.	200			
R.P.M.	1800			
M.P.H.	120			
Approx. dia. (Fig. 9)	8.2			
Approx. $\frac{V}{nD} = \frac{88 \times M.P.H.}{N\ D}$	.716			
Approx. $\frac{P}{D}$ (Fig. 10)	.746			
$1 - s = \frac{V}{nD}/\frac{P}{D}$	.96			
Approx. Tip Speed = .0524 ND	775			
$\frac{B.HP.}{C.HP.}$ (Fig. 7)	1.08			
Form factor	1			
$Q.HP. = \dfrac{B.HP.}{Form\ factor \times \frac{B.HP.}{C.HP.}}$	185			
K_s (Fig. 8)	2.07			
AR	7			
AR correction, Fig. 2	1.076			
CR	1.2			
CR correction, Fig. 3	.90			

TABLE III (Cont.)

	Approx.	Final	Approx.	Final
$K_s' = \dfrac{K_s}{AR \text{ cor.} \times CR \text{ cor.}}$	2.14			
$\dfrac{V}{nD}$ Fig. 1	.71			
$D = \dfrac{88 \times M.P.H.}{N \times \dfrac{V}{nD}}$	8.26 ft.			
$\dfrac{P}{D} = \dfrac{\dfrac{V}{nD}}{1-s}$	.74			
$P = D \times \dfrac{P}{D}$	6.11 ft.			
Notes	Service Prop.			

Fig.1 Speed-power coefficient for propeller analysis of standard Navy wood propellers

AR=6 and CR=1

Based on N.A.C.A. Navy model tests.

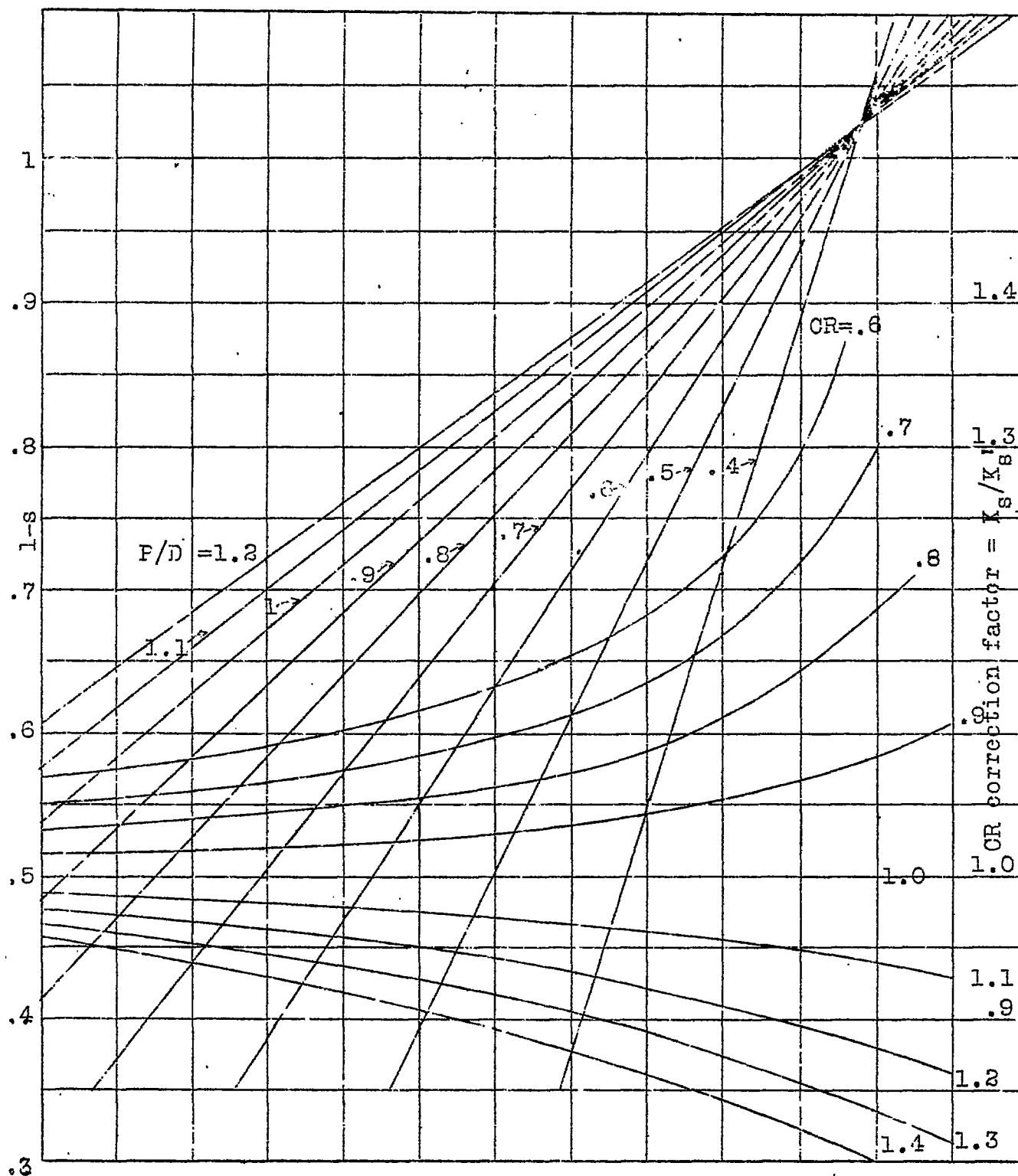Fig.2 Aspect ratio correction factor for K_g

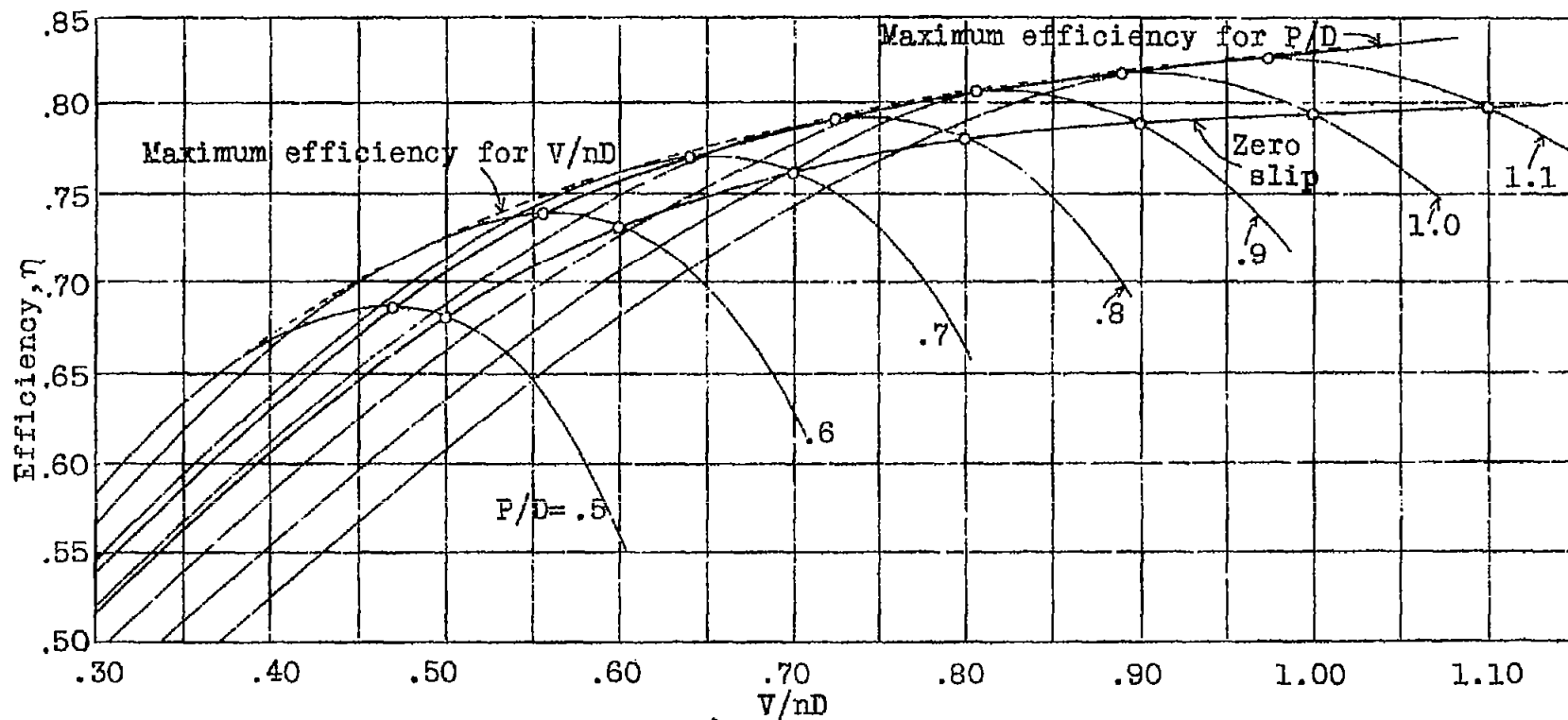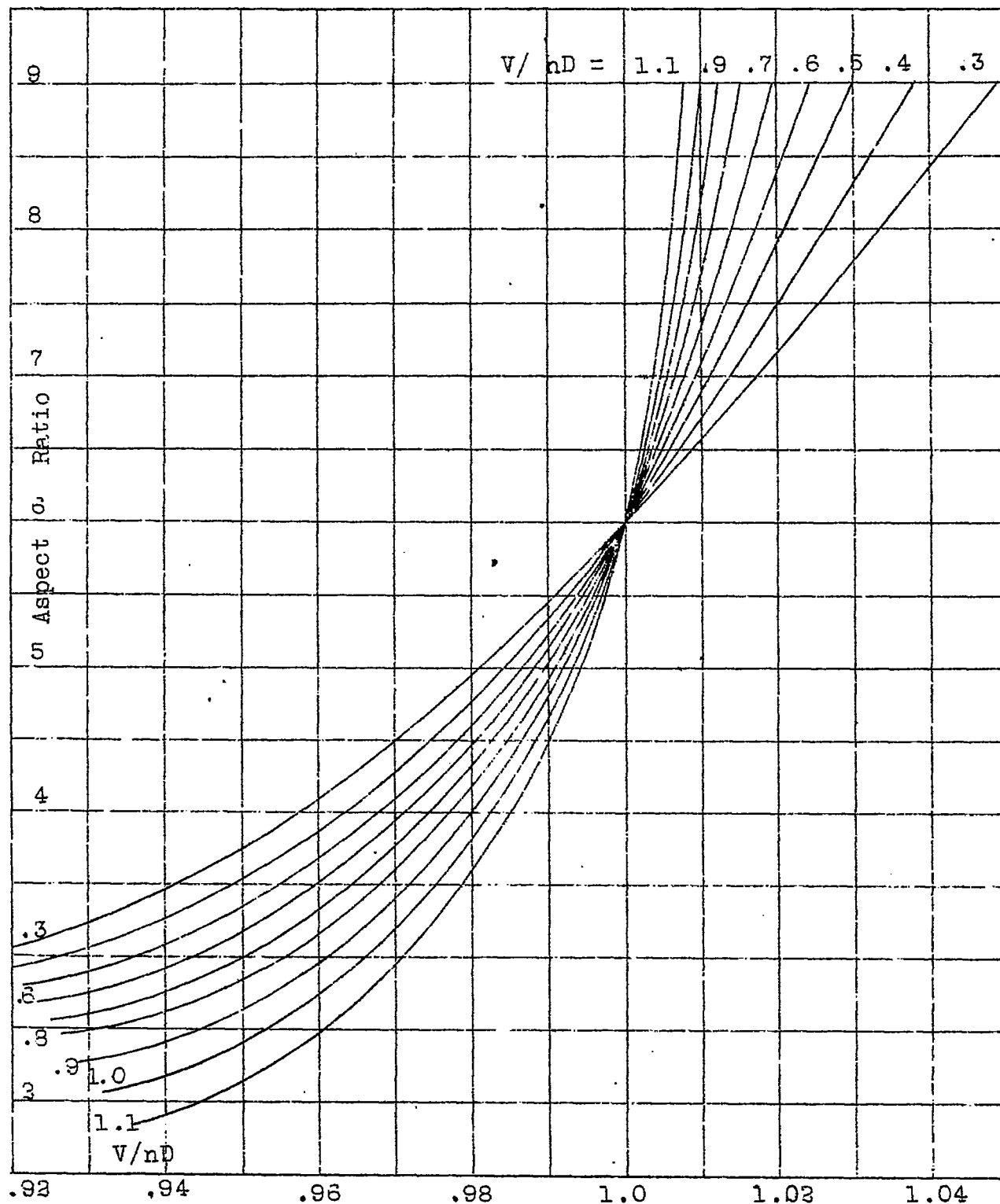Fig.3 Camber ratio correction factor for K_s

Fig.4

Fig.4   Propeller efficiencies for various P/D ratios and V/nD, for CR=1 and AR=6. Data from Durand's Navy model tests.

Fig.5   Aspect ratio correction factor for efficiency

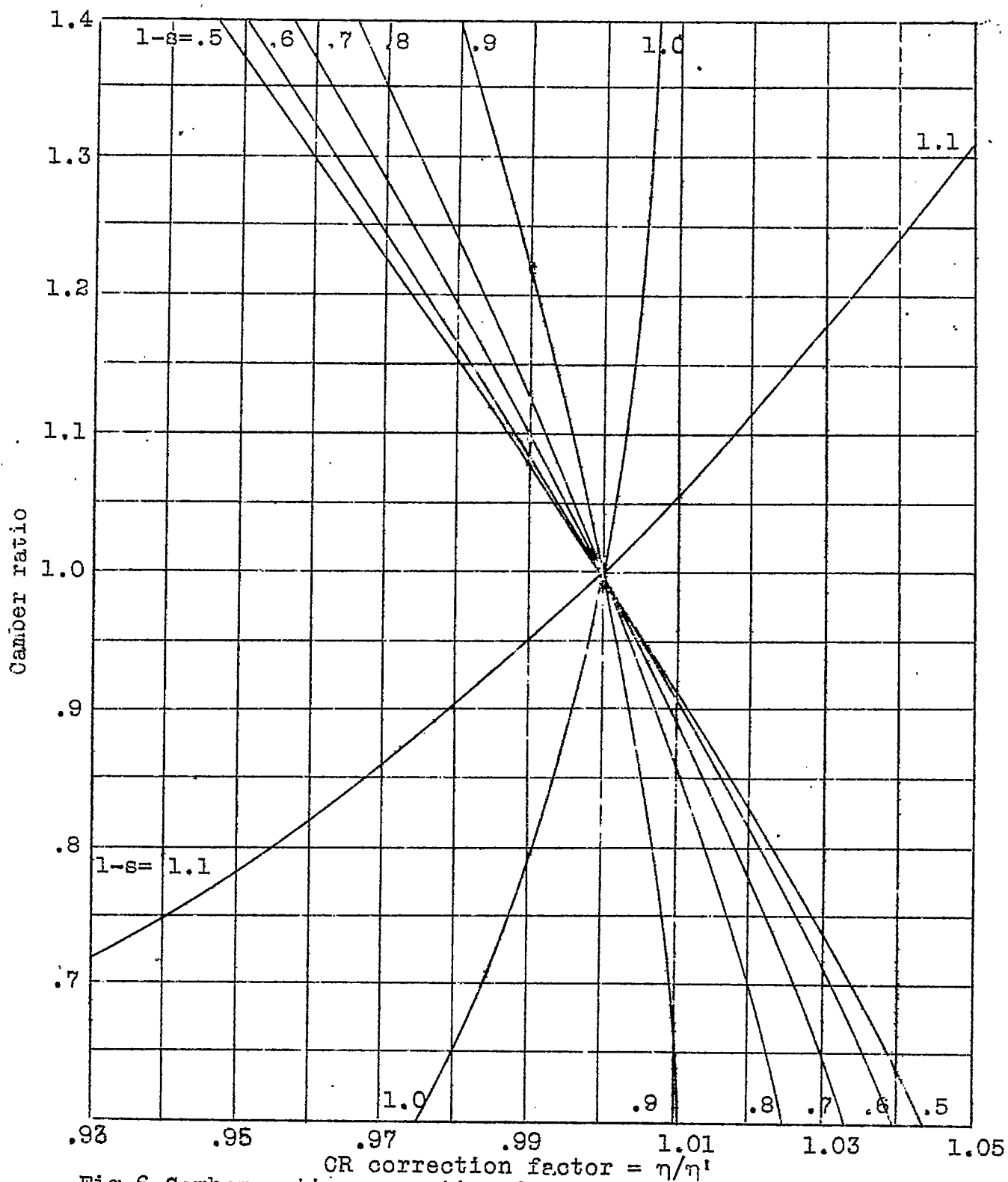Fig.6 Camber ratio correction factor for efficiency.

Note:- Curve shown for average tractor body.
MO-1 is 5% higher than average.

PN-7 is 5% lower than average.
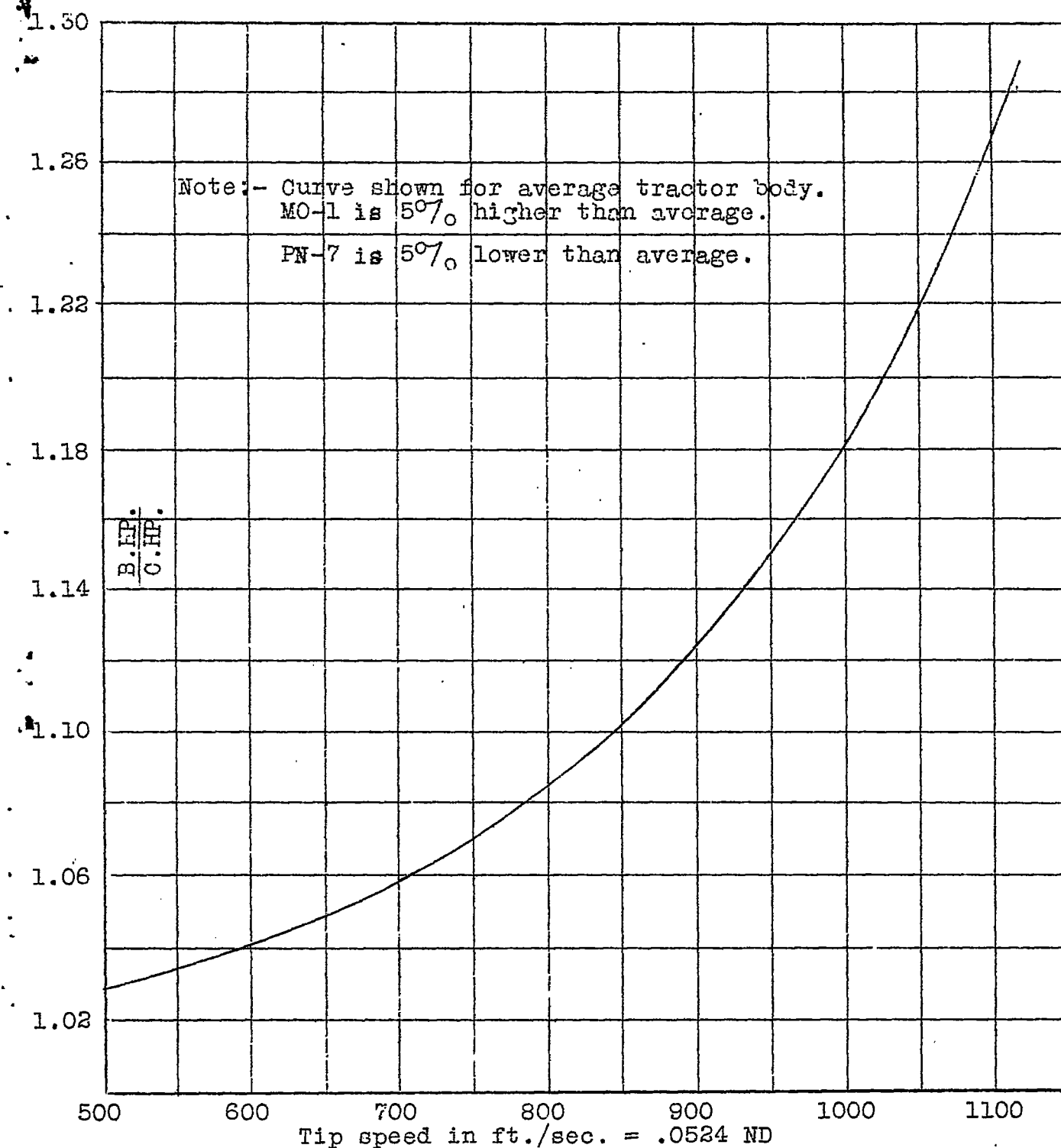
Fig.7 Horsepower factor for propeller scale effect and body
interference, from N.A.C.A. Tech. Note No.225.

SPEED—POWER COEFFICIENT

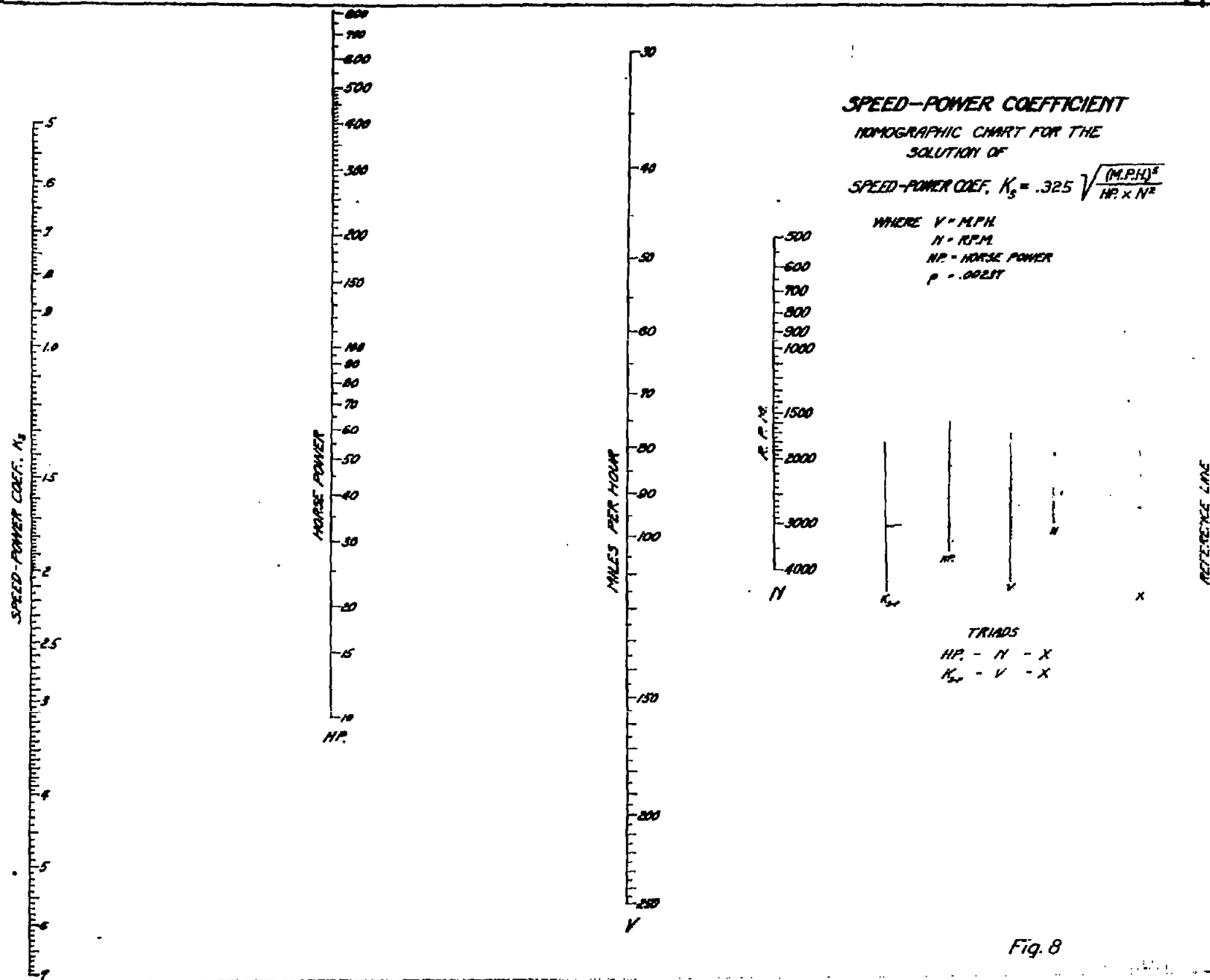NOMOGRAPHIC CHART FOR THE

SOLUTION OF

$$SPEED\text{—}POWER\ COEF.\ K_s = .325 \sqrt{\frac{(M.P.H.)^5}{HP. \times N^2}}$$

WHERE V = M.P.H.
         N = R.P.M.
         HP = HORSE POWER
         p = .00238

TRIADS

HP. — N — X
K_{sp} — V — X

Fig. 8

Fig. 8

- PROPELLER DIAMETER -

NOMOGRAPHIC CHART FOR
SOLUTION OF EQUATION

$$D = K \sqrt[4]{\frac{HP}{N^2 V}}$$

WHERE D = DIAMETER IN FT.
HP = HORSE POWER
N = R.P.M.
V = VELOCITY IN M.P.H.

VALUES OF K

	2-BLADED	3-BLADED	4-BLADED
SPEED (OPTIMUM SLIP)	225	252	270
CLIMB (20% SLIP)	230	261	270
SERVICE	245	275	260

1. DIAMETER ESTIMATE FOR WOODEN
PROPELLERS ONLY.

2. A THREE BLADED METAL PROPELLER
REQUIRED APPROXIMATELY THE SAME
DIAMETER AS A TWO-BLADED WOODEN ONE.

TURNS

N - X - V
HP - Y - X
Y - D - K

Fig 9

Fig. 9

Curves based on CR = 1.0
for each .1 CR above 1 sub..01 from V/nD
  "   "   "   " below 1 add..01 to   "
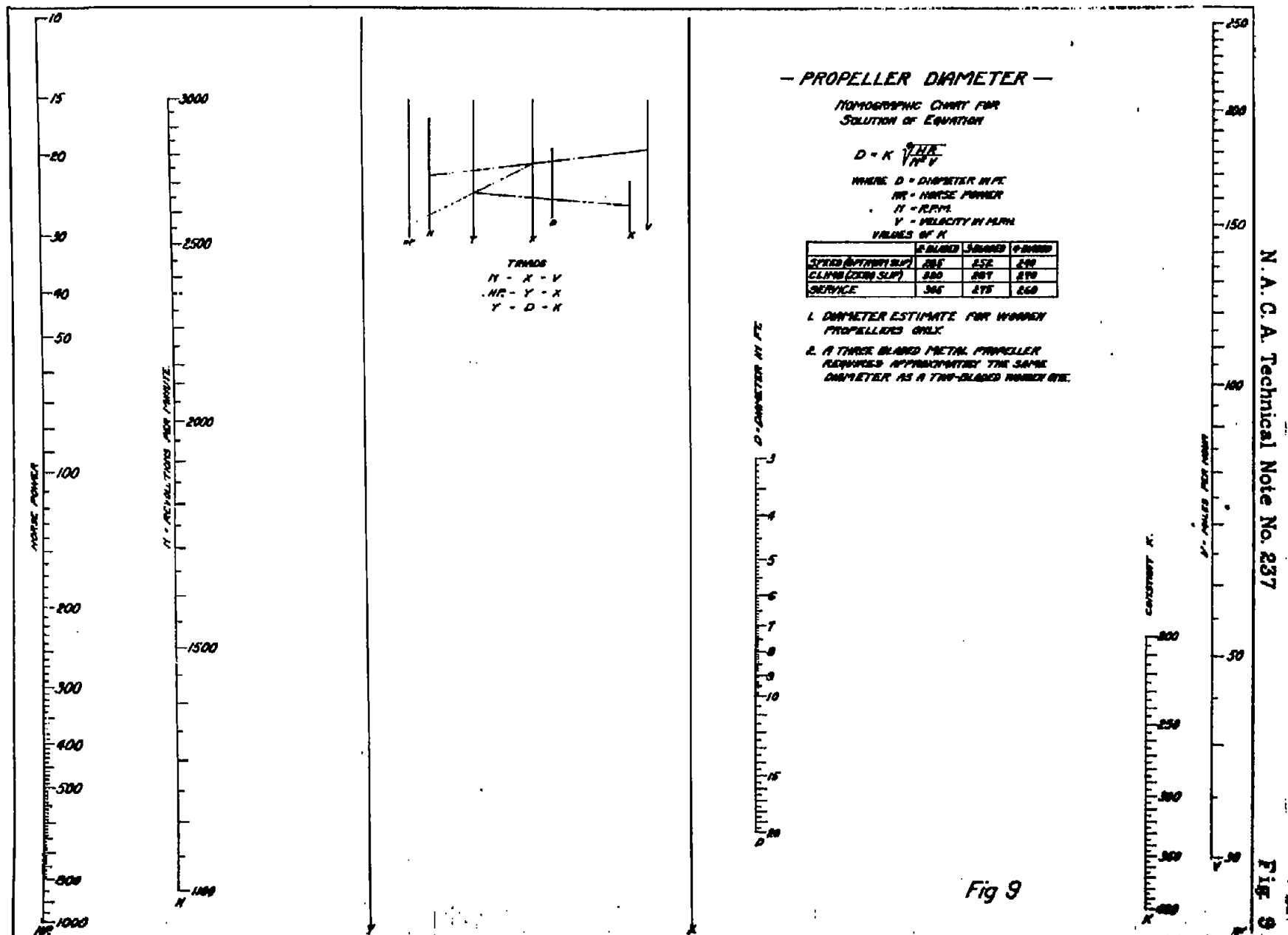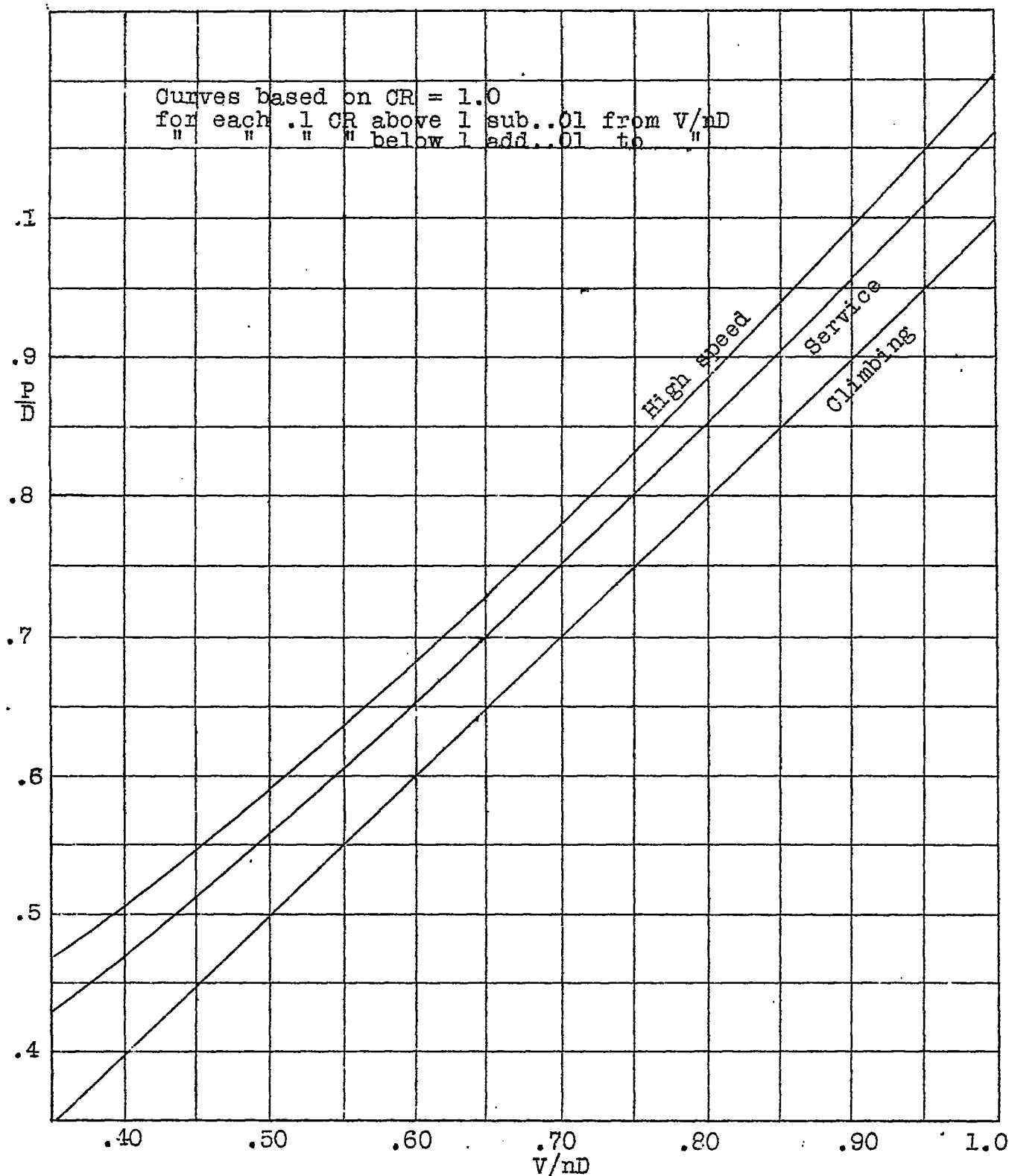

Fig.10 Combinations of P/D and V/nD for high speed, climbing and
       service propellers.

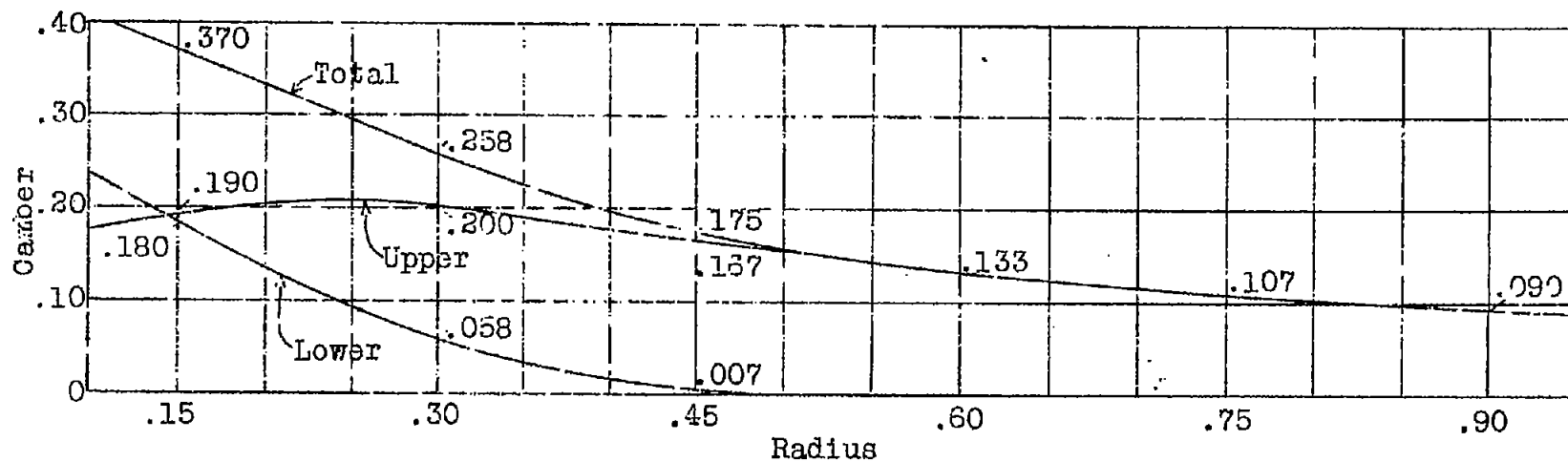Fig.11 Camber-ratio curve for CR=1.   Wooden propellers.

Fig.11

Fig.12

.900   b/c   .945   1.00   .945

.792

.540

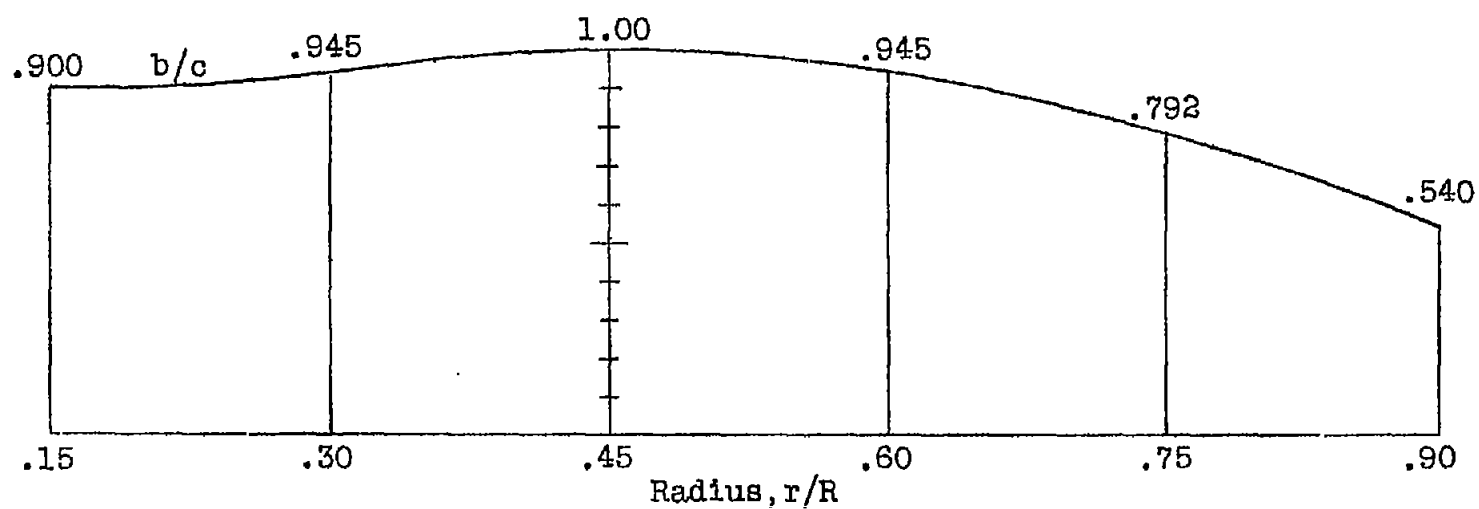.15   .30   .45   .60   .75   .90

Radius, r/R

Fig.12 Standard Navy plan form for wooden propellers.